



(12) **United States Patent**  
**Janssen et al.**

(10) **Patent No.:** **US 9,194,273 B2**  
(45) **Date of Patent:** **Nov. 24, 2015**

(54) **APPARATUS, SYSTEM, AND METHOD FOR  
AFTERTREATMENT CONTROL AND  
DIAGNOSTICS**

(75) Inventors: **John M. Janssen**, Henrico, VA (US);  
**Frederick H. Lindner**, North Vernon,  
IN (US); **Matthew L. Schneider**,  
Seymour, IN (US)

(73) Assignee: **Cummins Inc.**, Columbus, IN (US)

(\*) Notice: Subject to any disclaimer, the term of this  
patent is extended or adjusted under 35  
U.S.C. 154(b) by 168 days.

(21) Appl. No.: **13/541,137**

(22) Filed: **Jul. 3, 2012**

(65) **Prior Publication Data**

US 2014/0007559 A1 Jan. 9, 2014

**Related U.S. Application Data**

(63) Continuation of application No. 12/610,830, filed on  
Nov. 2, 2009, now Pat. No. 8,223,337.

(60) Provisional application No. 61/197,897, filed on Oct.  
31, 2008, provisional application No. 61/197,898,  
filed on Oct. 31, 2008.

(51) **Int. Cl.**

**F01N 3/00** (2006.01)

**F01N 3/02** (2006.01)

**F01N 3/10** (2006.01)

**F01N 3/20** (2006.01)

**F01N 11/00** (2006.01)

(Continued)

(52) **U.S. Cl.**

CPC ..... **F01N 11/00** (2013.01); **F01N 3/0814**  
(2013.01); **F01N 3/106** (2013.01); **F01N 3/206**  
(2013.01); **F01N 9/005** (2013.01); **F01N 3/035**

(2013.01); **F01N 3/2066** (2013.01); **F01N**  
**13/008** (2013.01); **F01N 13/009** (2014.06);  
**F01N 2250/02** (2013.01); **F01N 2550/00**  
(2013.01); **F01N 2550/03** (2013.01); **F01N**  
**2550/04** (2013.01); **F01N 2550/05** (2013.01);  
**F01N 2560/02** (2013.01); **F01N 2560/021**  
(2013.01); **F01N 2560/05** (2013.01); **F01N**  
**2560/14** (2013.01); **F01N 2610/02** (2013.01);  
**F01N 2900/0416** (2013.01); **F01N 2900/1402**  
(2013.01); **F01N 2900/1821** (2013.01); **G01M**  
**15/10** (2013.01); **Y02T 10/47** (2013.01)

(58) **Field of Classification Search**

USPC ..... 60/286, 295, 274, 277, 301, 324  
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,578,762 A 3/1986 Wong  
4,694,173 A 9/1987 Wong

(Continued)

*Primary Examiner* — Audrey K Bradley

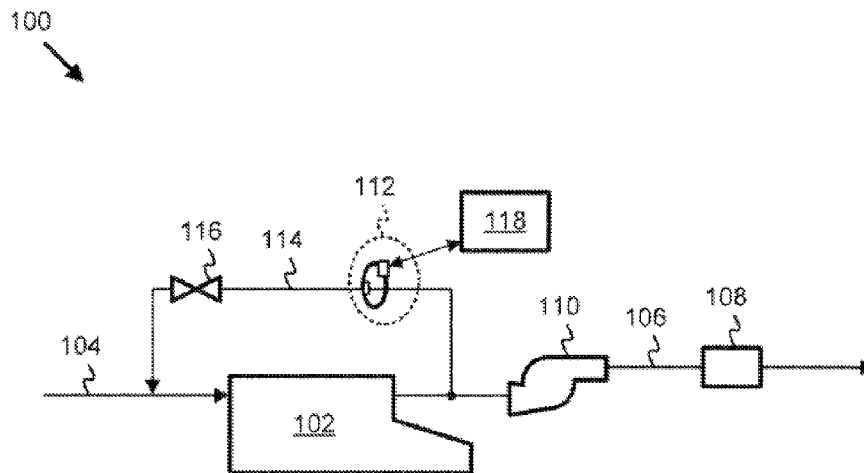
*Assistant Examiner* — Dapinder Singh

(74) *Attorney, Agent, or Firm* — Taft, Stettinius & Hollister  
LLP

(57) **ABSTRACT**

A method includes providing an exhaust stream for an internal combustion engine, where the exhaust stream is fluidly coupled to an aftertreatment component. The method includes optically determining an amount of an exhaust gas constituent in the exhaust stream. The method further includes modifying a model stored on a computer readable medium in response to the amount of the exhaust gas constituent. The model is an engine NO<sub>x</sub> generation model, a catalyst NO<sub>x</sub> storage model, a catalyst NO<sub>x</sub> conversion model, a catalyst NO to NO<sub>2</sub> conversion model, a catalyst conversion efficiency model, an engine soot generation model, and/or a urea hydrolysis model.

**15 Claims, 14 Drawing Sheets**



(51)	<b>Int. Cl.</b>		6,330,794 B1	12/2001	Caren et al.
	<b>F01N 3/08</b>		6,344,798 B1	2/2002	Schell
	<b>F01N 9/00</b>		6,357,223 B1	3/2002	Caren et al.
	<b>G01M 15/10</b>		6,810,660 B2	11/2004	Hepburn et al.
	<b>F01N 13/00</b>		6,810,718 B2	11/2004	Wilson et al.
(56)	<b>References Cited</b>		6,842,243 B2	1/2005	Tokhtuev et al.
	<b>U.S. PATENT DOCUMENTS</b>		6,917,038 B2	7/2005	Zheng et al.
	4,756,622 A	7/1988 Wong	6,982,431 B2	1/2006	Modlin et al.
	4,795,240 A	1/1989 Wong	7,007,547 B2	3/2006	Philipp et al.
	4,850,697 A	7/1989 Schoennauer	7,084,963 B2	8/2006	Leipertz
	4,924,095 A	5/1990 Swanson	7,176,460 B1	2/2007	Wong
	5,241,367 A	8/1993 Grob	7,178,331 B2	2/2007	Blakeman et al.
	5,464,982 A	11/1995 Drucker	7,186,979 B1	3/2007	Wong
	5,464,983 A	11/1995 Wang	7,214,939 B1	5/2007	Wong
	5,583,339 A	12/1996 Black et al.	7,240,482 B2	7/2007	Hepburn et al.
	5,617,720 A	4/1997 Achleitner et al.	7,264,785 B2	9/2007	Blakeman et al.
	5,699,077 A	12/1997 Hosotani	7,313,911 B2	1/2008	Pfeifer et al.
	5,748,311 A	5/1998 Hamann et al.	7,409,823 B2	8/2008	Price et al.
	5,767,776 A	6/1998 Wong	7,480,044 B2	1/2009	Leipertz
	5,798,700 A	8/1998 Wong	7,991,533 B2 *	8/2011	Huang ..... 701/101
	5,834,777 A	11/1998 Wong	8,218,147 B2	7/2012	Janssen et al.
	5,889,199 A	3/1999 Wong et al.	8,223,337 B2	7/2012	Janssen et al.
	5,894,373 A	4/1999 Wong	2002/0154289 A1	10/2002	Wilks, Jr.
	5,945,924 A	8/1999 Marman et al.	2004/0237505 A1	12/2004	Leipertz
	6,047,543 A	4/2000 Caren et al.	2005/0076655 A1	4/2005	Wong
	6,048,500 A	4/2000 Caren et al.	2005/0247066 A1	11/2005	Myhre
	6,107,925 A	8/2000 Wong	2006/0251548 A1	11/2006	Willey et al.
	6,166,647 A	12/2000 Wong	2006/0256330 A1	11/2006	Leipertz
	6,237,575 B1	5/2001 Lampert et al.	2007/0029487 A1	2/2007	Wong et al.
	6,247,303 B1 *	6/2001 Broer et al. .... 60/274	2007/0029488 A1	2/2007	Wong
	6,253,544 B1	7/2001 Miller et al.	2007/0068495 A1	3/2007	Karst
	6,264,899 B1	7/2001 Caren et al.	2008/0264039 A1 *	10/2008	Lattin et al. .... 60/285
	6,321,531 B1	11/2001 Caren et al.	2008/0295499 A1	12/2008	Driscoll et al.
			2008/0306631 A1 *	12/2008	Huang ..... 700/271
			2009/0193794 A1	8/2009	Robel et al.
			2010/0008363 A1	1/2010	Ee et al.
			2010/0101213 A1	4/2010	Tuomivaara et al.

\* cited by examiner

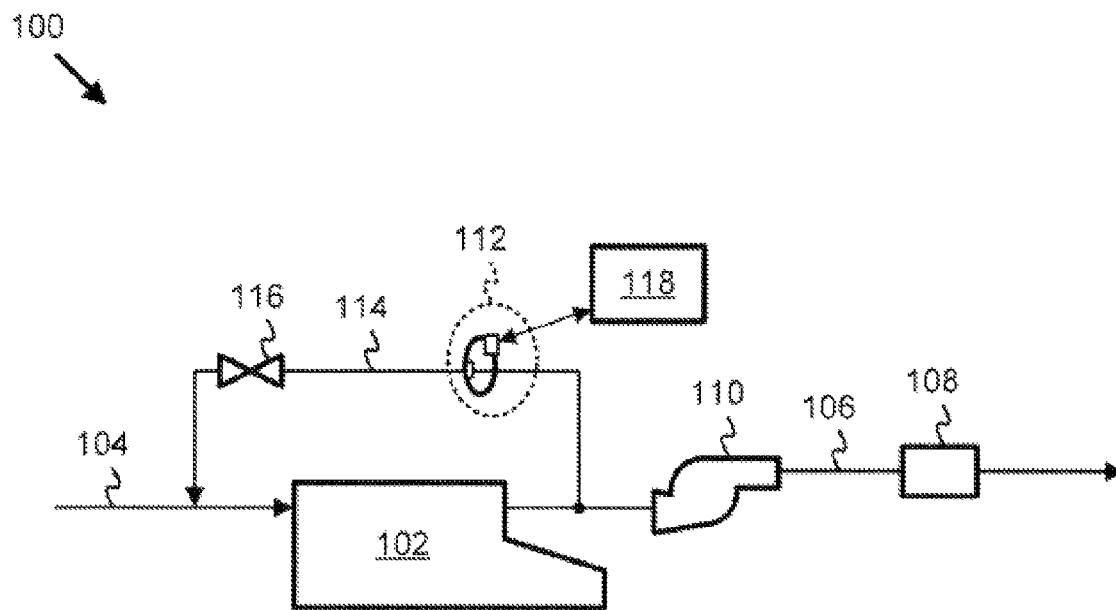


Fig. 1

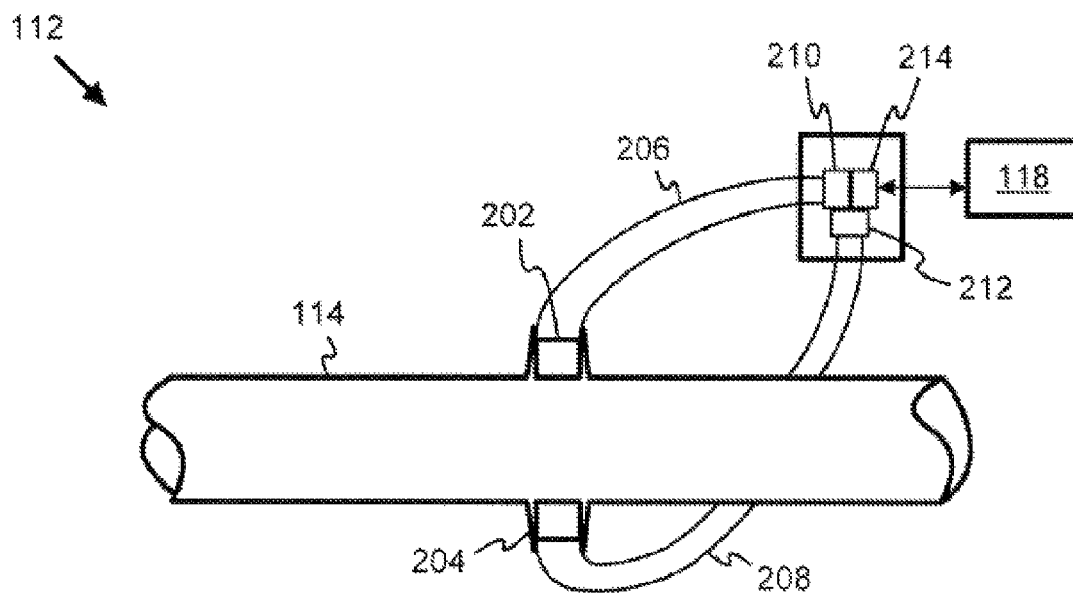


Fig. 2

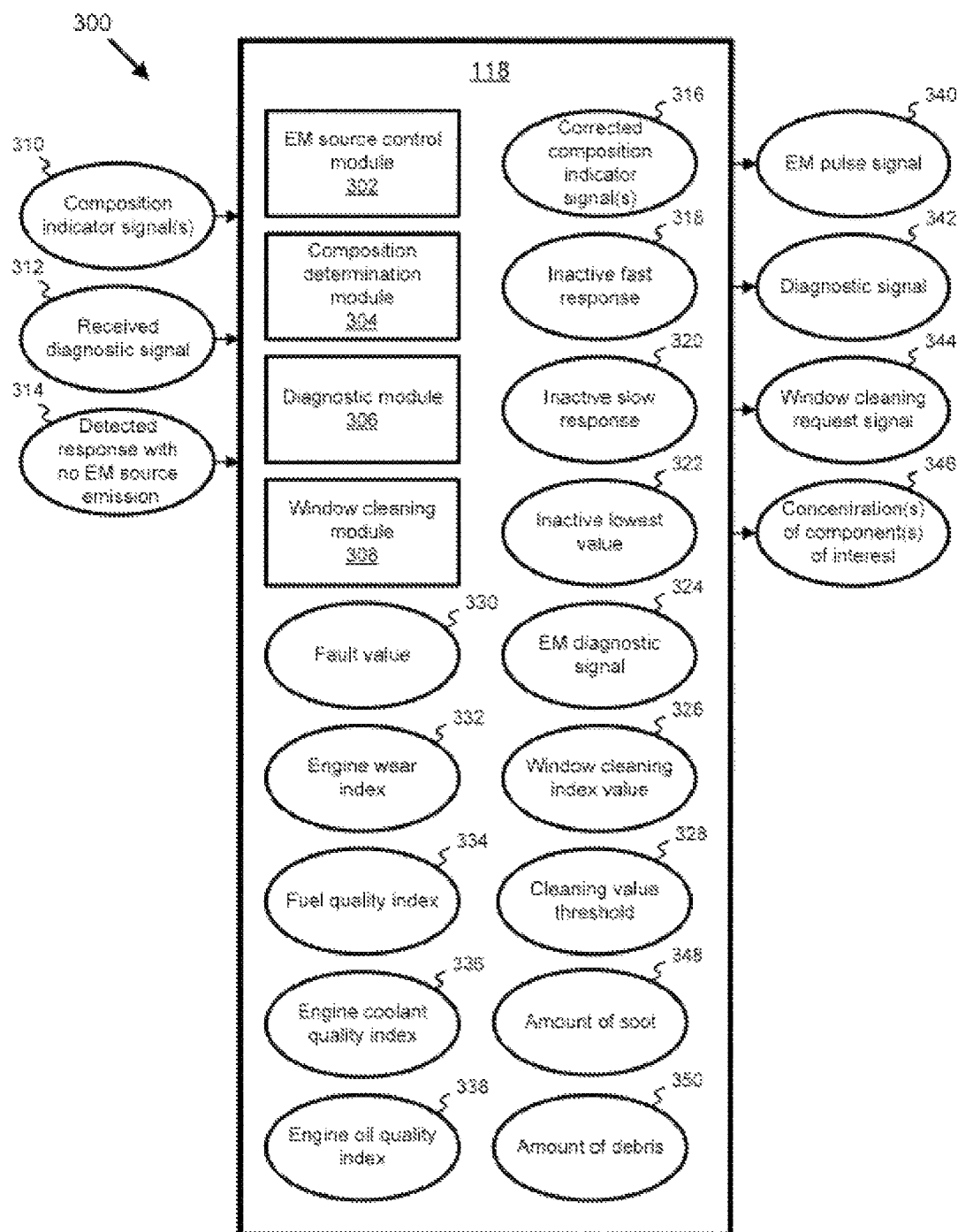


Fig. 3

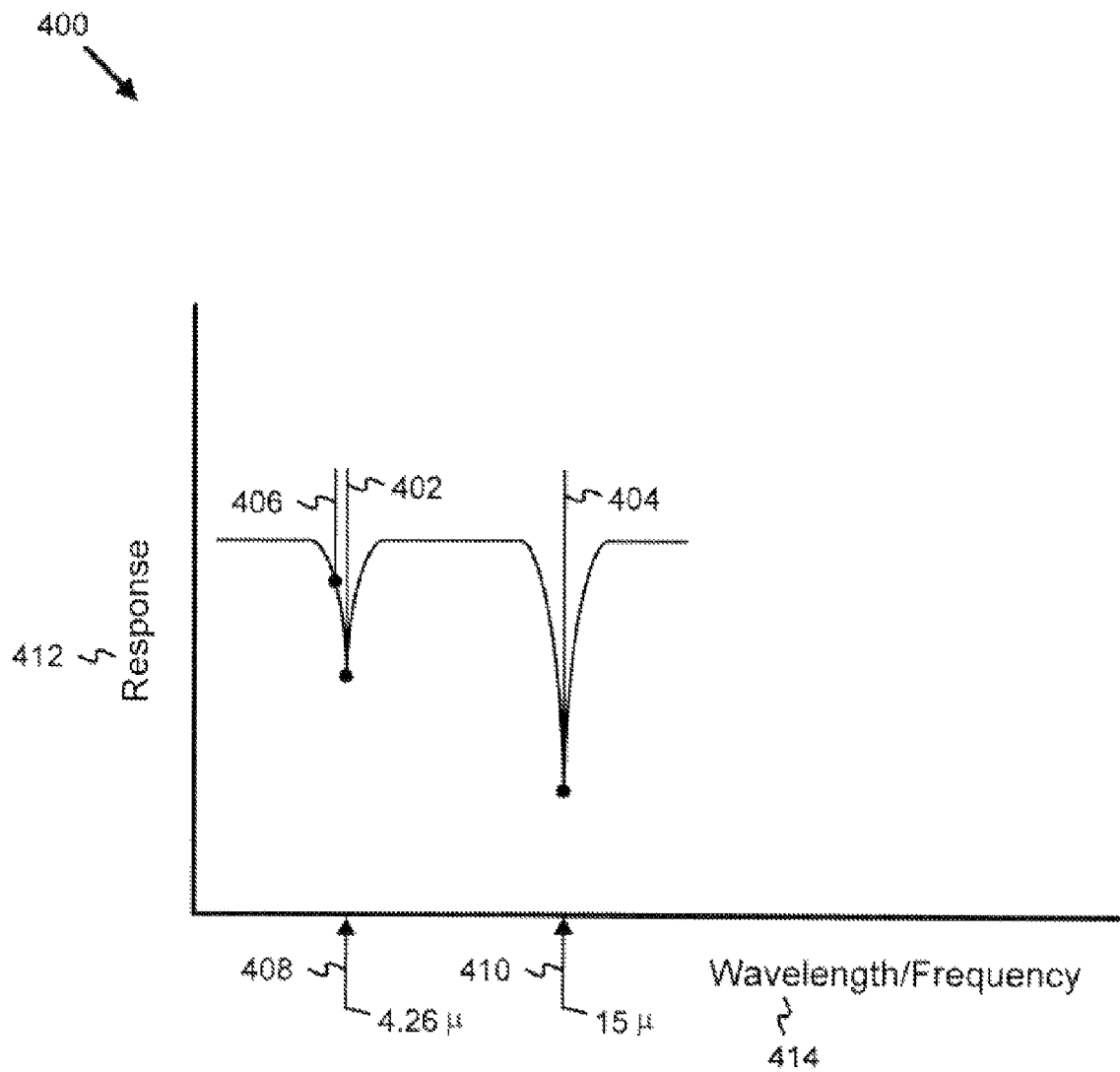


Fig. 4

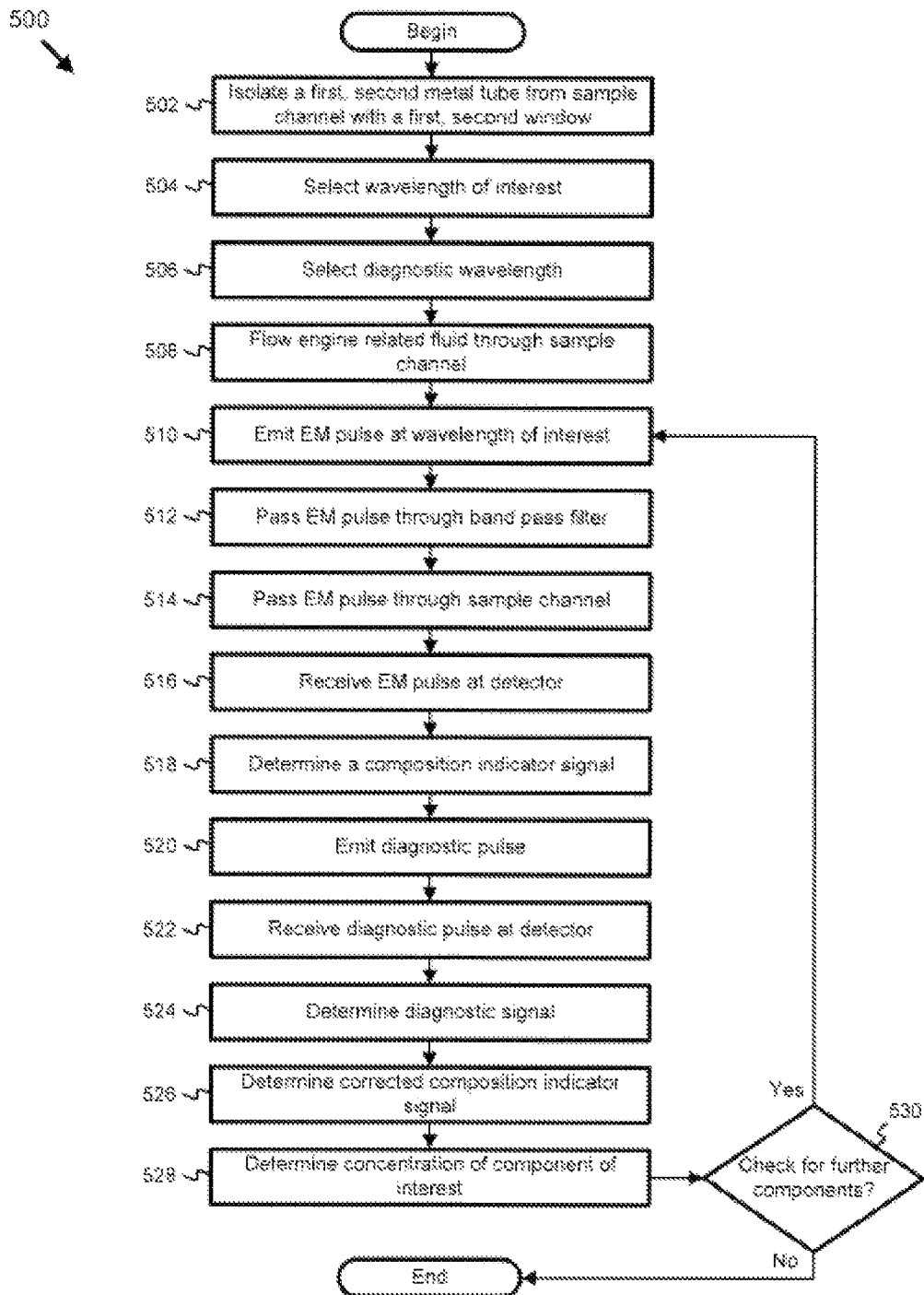


Fig. 5

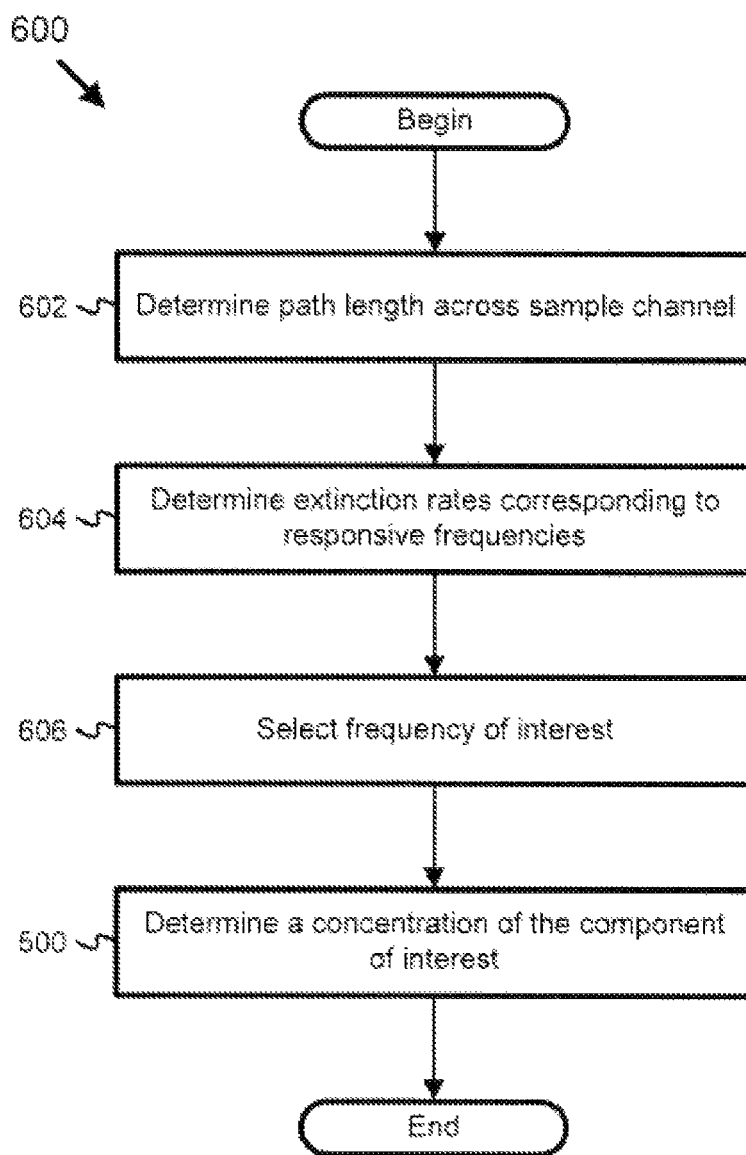


Fig. 6

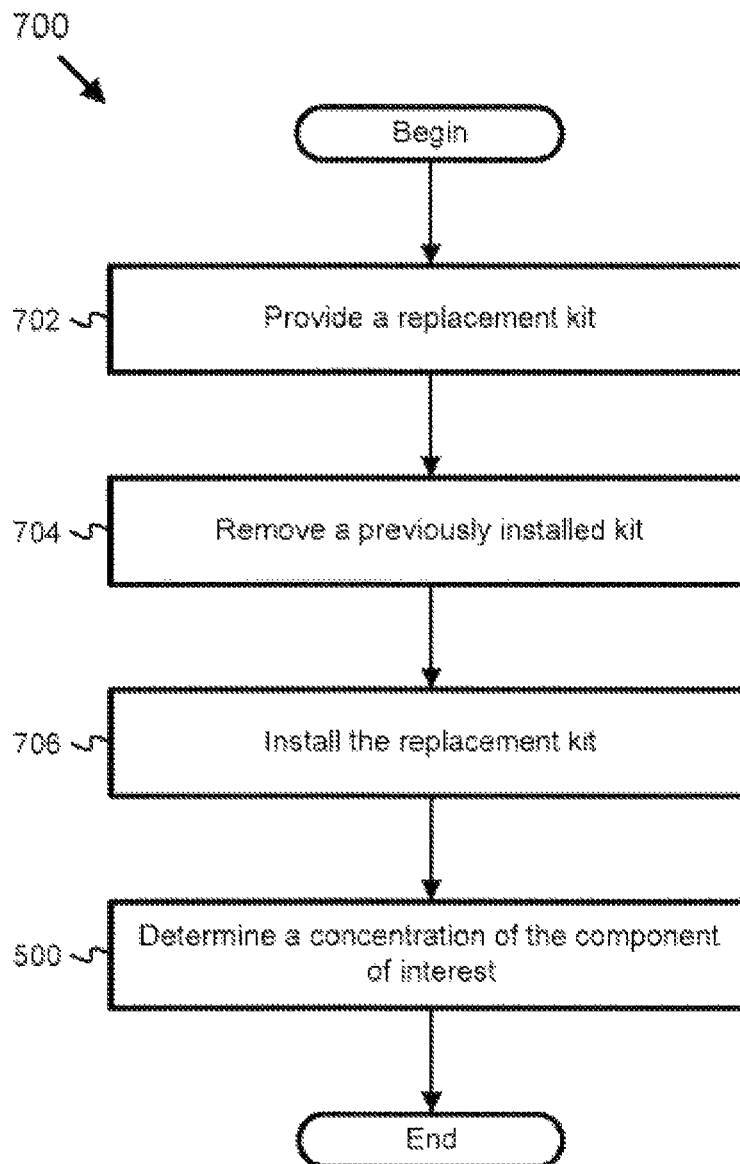


Fig. 7



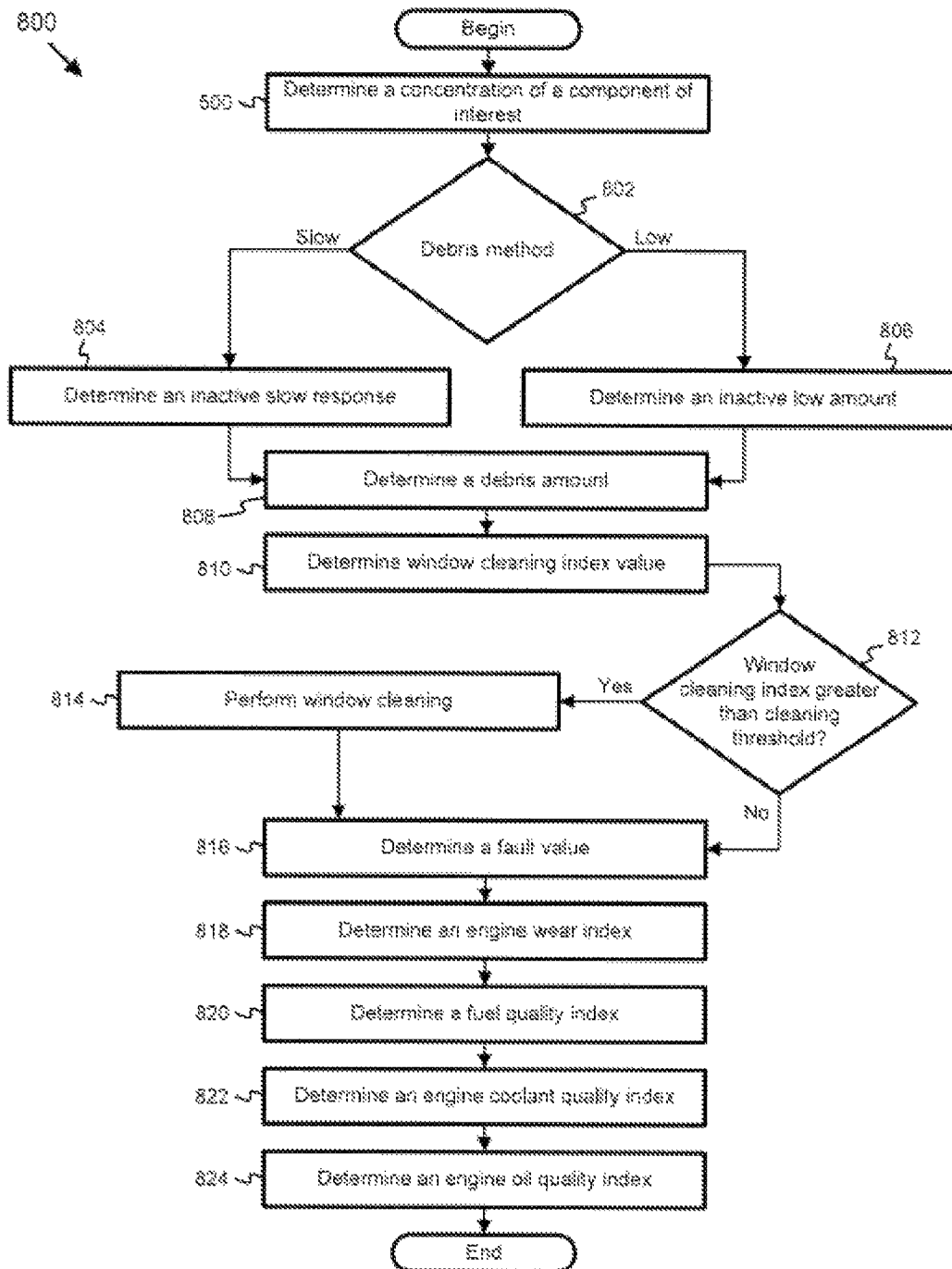


Fig. 8

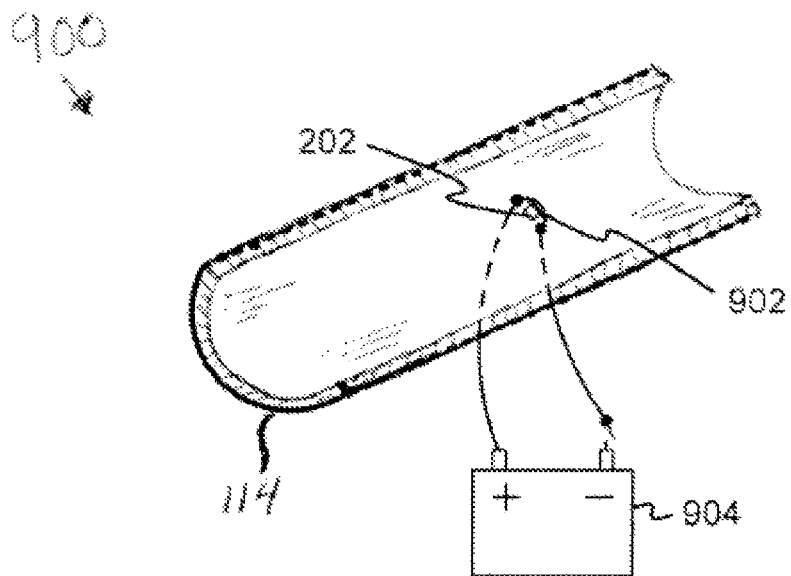


Fig. 9A

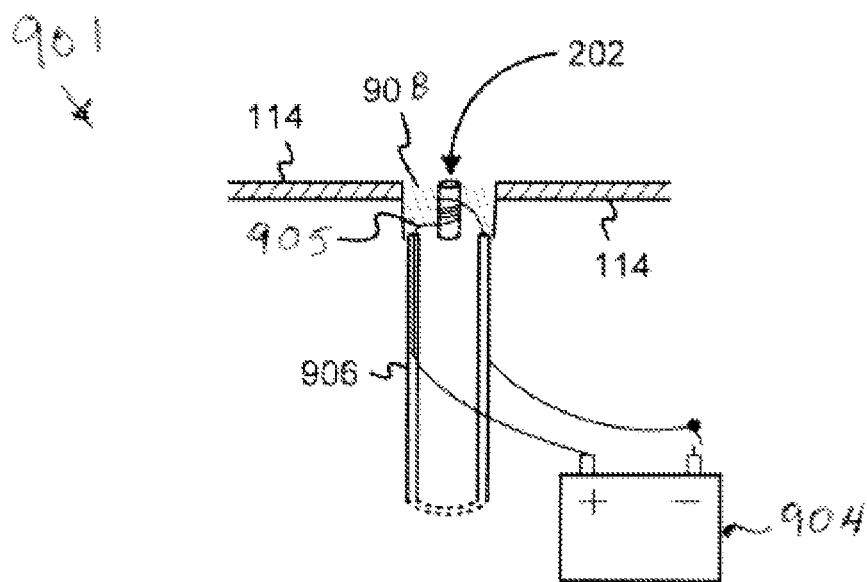


Fig. 9B

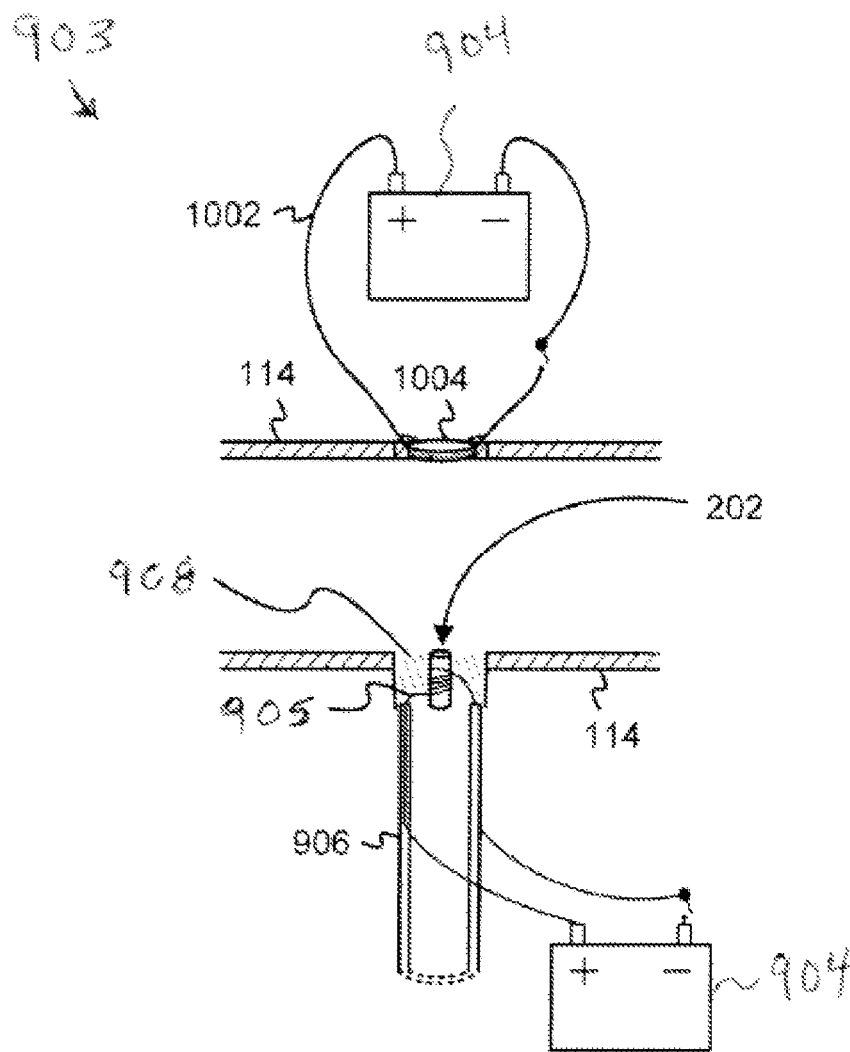


Fig. 9C

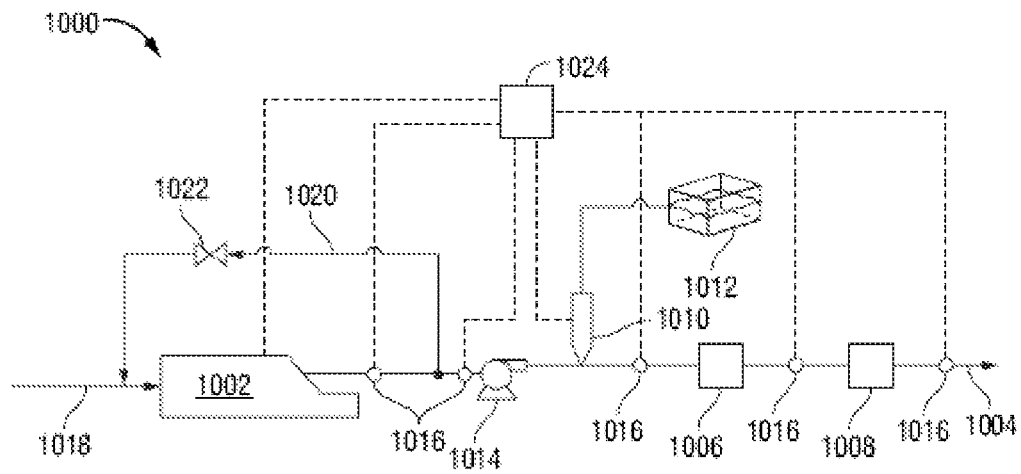


Fig. 10

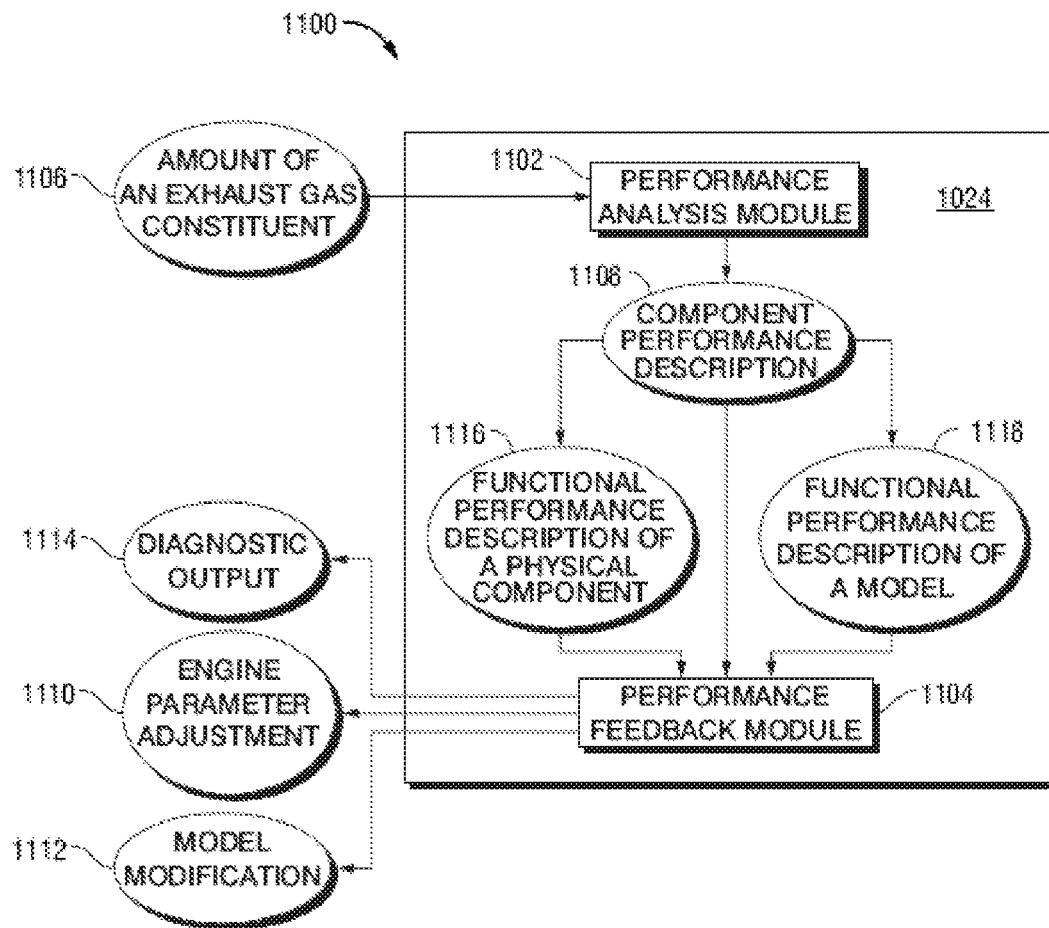


Fig. 11

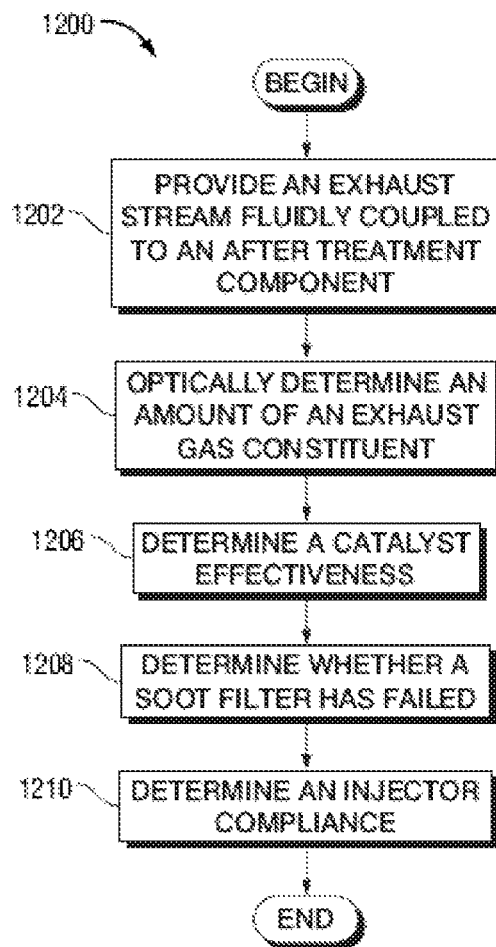


Fig. 12

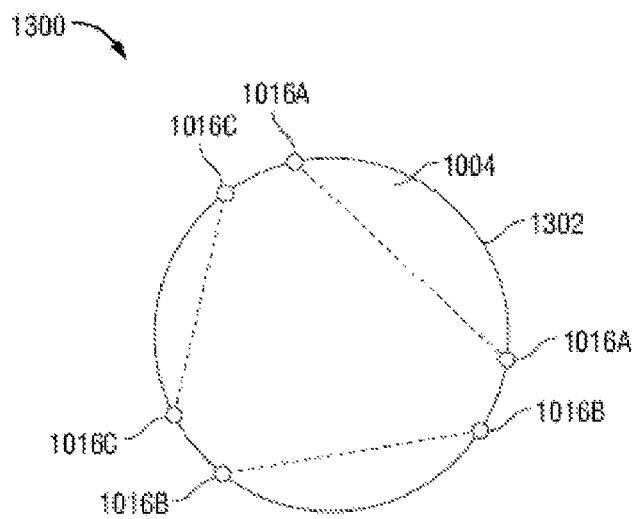


Fig. 13

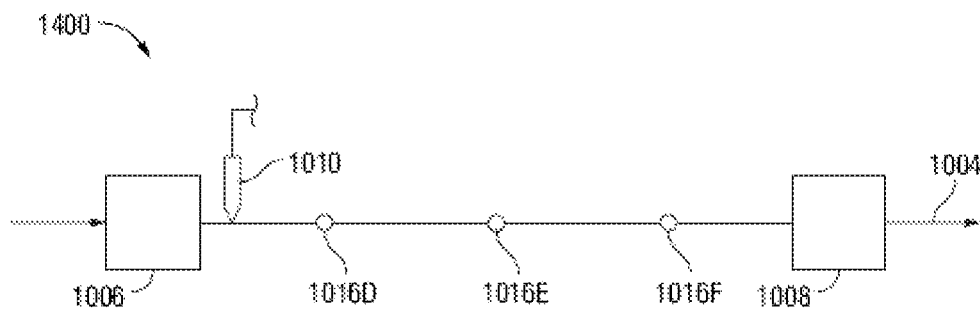


Fig. 14

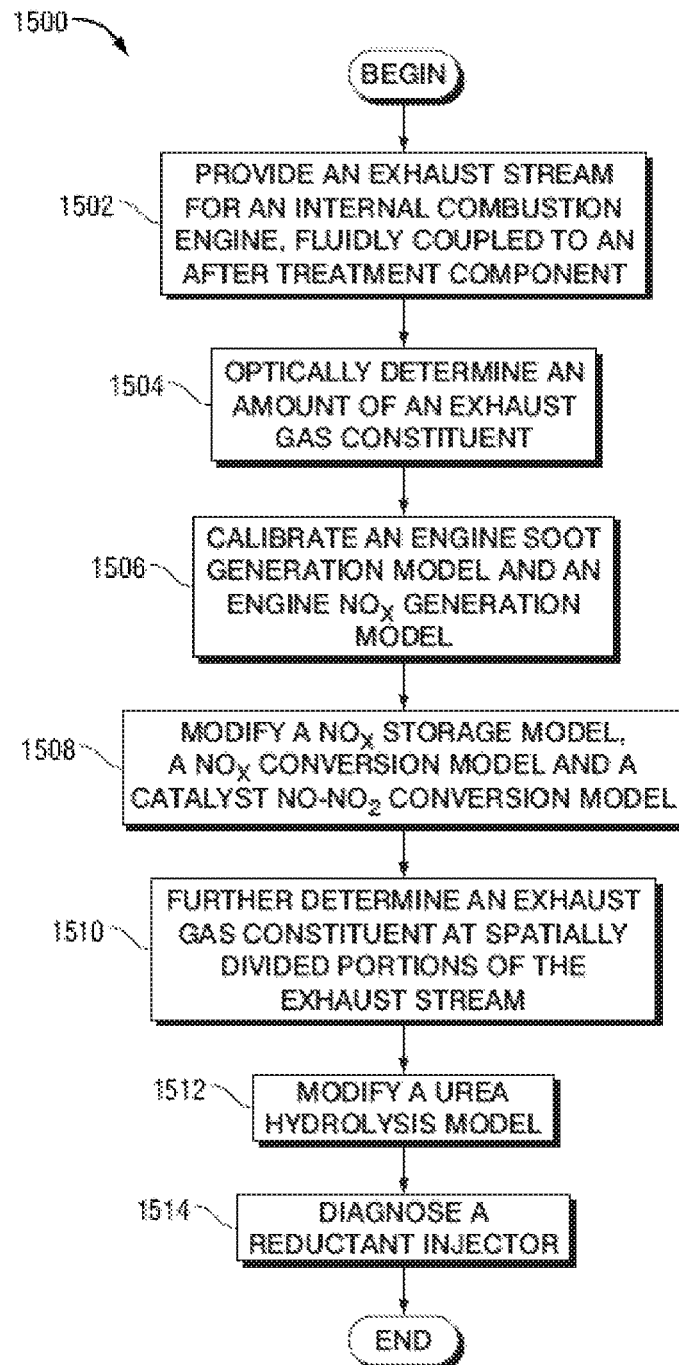


Fig. 15



1

# APPARATUS, SYSTEM, AND METHOD FOR AFTERTREATMENT CONTROL AND DIAGNOSTICS

## RELATED APPLICATION

The present application is a continuation of U.S. patent application Ser. No. 12/610,830 filed on Nov. 2, 2009, now U.S. Pat. No. 8,223,337, which claims the benefit of U.S. Provisional Patent Application No. 61/197,897 and U.S. Provisional Patent Application No. 61/197,898 both filed on Oct. 31, 2008, each of which are hereby incorporated by reference in the entirety for all purposes.

## BACKGROUND

Reliably monitoring exhaust gas constituents related to aftertreatment systems for internal combustion engines presents several challenges. Frequently, exhaust environments operate at very high temperatures that preclude use of many standard sensor types. Further, engine combustion constituents typically include soot and unburned hydrocarbons that can hamper operation of various sensing technologies. Present sensing technologies cannot detect various constituents of the exhaust gas and survive the exhaust environment. Various aftertreatment systems and technologies for internal combustion engines experience wear, failure, and operational variability that affect the final emissions of the engine-aftertreatment system. Presently available sensing technologies have very limited feedback for aftertreatment systems, making control and diagnostics for aftertreatment systems difficult. Thus, there is an ongoing demand for further contributions in this area.

## SUMMARY

One embodiment is a unique method for determining an aftertreatment component performance in response to an optically determined exhaust gas constituent amount, and modifying and engine operating parameter in response to the aftertreatment component performance. Further embodiments, forms, objects, features, advantages, aspects, and benefits shall become apparent from the following description and drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram of a system for detecting engine fluid constituents.

FIG. 2 is a schematic illustration of an device for detecting engine fluid constituents.

FIG. 3 is a schematic diagram of a controller structured to determine a concentration of a component of interest.

FIG. 4 is an illustration of a constituent wavelength response.

FIG. 5 is a schematic flow diagram of a procedure for determining a concentration of a component of interest.

FIG. 6 is a schematic flow diagram of a procedure for designing an apparatus for determining a concentration of a component of interest.

FIG. 7 is a schematic flow diagram of a procedure for replacing an apparatus for determining a concentration of a component of interest.

FIG. 8 is a schematic flow diagram of a procedure for determining a plurality of fluid indices.

FIG. 9A is a schematic diagram of an apparatus for cleaning an optical element.

2

FIG. 9B is a schematic diagram of an apparatus for cleaning an optical element.

FIG. 9C is a schematic diagram of an apparatus for cleaning an optical element.

FIG. 10 is a schematic diagram of a system for determining a component performance and adjusting an engine operating parameter.

FIG. 11 is a schematic diagram of a component performance controller.

FIG. 12 is a schematic flow diagram of a technique for diagnosing a component.

FIG. 13 is a schematic diagram of an apparatus to determine an exhaust gas constituent at spatially divided portions of an exhaust stream.

FIG. 14 is a schematic diagram of another apparatus to determine an exhaust gas constituent at spatially divided portions of the exhaust stream.

FIG. 15 is a schematic flow diagram of a technique for modifying a model in response to an amount of an exhaust gas constituent.

## DESCRIPTION OF THE ILLUSTRATIVE EMBODIMENTS

For the purposes of promoting an understanding of the principles of the invention, reference will now be made to the embodiments illustrated in the drawings and specific language will be used to describe the same. It will nevertheless be understood that no limitation of the scope of the invention is thereby intended, any alterations and further modifications in the illustrated embodiments, and any further applications of the principles of the invention as illustrated therein as would normally occur to one skilled in the art to which the invention relates are contemplated and protected.

FIG. 10 is a schematic diagram of a system 1000 for determining a component performance and adjusting an engine operating parameter. The system includes an internal combustion engine 1002 producing an exhaust stream 1004 and having aftertreatment components 1006, 1008. The exemplary system 1000 includes a turbocharger 1014 and an exhaust gas recirculation (EGR) stream 1020 with an EGR valve 1022 that controls a flow rate of EGR. The system 1000 includes an intake stream 1018 for the internal combustion engine 1002. The system includes an injector 1010 that injects a reductant and/or reagent into the exhaust stream 1004, and a reductant (or reagent) storage vessel 1012. The storage vessel 1012 may be a urea storage vessel, a fuel tank of a vehicle wherein the internal combustion engine 1002 is installed, or any other vessel having a reductant (or reagent) known in the art.

The system 1000 includes a component performance controller 1024 in communication with one or more optical sensors 1016 to determine an amount of an exhaust gas constituent. Optical sensors 1016, as used herein, indicate any sensor utilizing electromagnetic waves in the infrared, visible, and ultraviolet frequency ranges of electromagnetic radiation. The placement of optical sensors 1016 is exemplary, and an optical sensor 1016 may be positioned anywhere within the system wherein an exhaust gas constituent determination is to be made. The amount of the exhaust gas constituent may be described as a fraction, percentage, concentration, or absolute mass of the constituent as understood in the art. The component performance controller 1024 may be in communication with any component of the system, and may further be an aftertreatment controller and/or the engine controller. The component performance controller 1024 may be a single

controller, a plurality of distributed controllers, and may have certain functionality implemented in hardware, software, or both.

FIG. 11 is a schematic diagram of an apparatus 1100 including a component performance controller 1024. The apparatus 1100 a performance analysis module 1102 that determines a component performance description 1108 in response to an amount of the exhaust gas constituent 1106 determined with an optical sensor 1016. The performance feedback module 1104 provides an engine parameter adjustment 1110 in response to the component performance description 1108. In certain embodiments, the component performance description 1108 is a functional performance description of a physical component 1116. For example, the physical component may be a NO<sub>x</sub> adsorption catalyst, a NO<sub>x</sub> conversion catalyst, an NO—NO<sub>2</sub> conversion catalyst, an oxidation catalyst, a soot filter, and/or a reductant injector. Non-limiting examples of the functional performance description of the physical component 1116 include a catalyst conversion efficiency value, a catalyst storage capacity value, a filter integrity value, and/or an injection compliance value.

In certain embodiments, the component performance description 1108 is a functional performance description of a model 1118, and the performance feedback module 1104 adjusts an engine operating parameter by providing a model modification 1112. Non-limiting examples of a model include an engine-out soot model, an engine-out NO<sub>x</sub> model, an engine-out NO<sub>x</sub> composition model, a NO<sub>x</sub> adsorption model, a NO<sub>x</sub> release model, a NO<sub>x</sub> conversion model, a hydrocarbon oxidation model, an ammonia slip model, an unburned hydrocarbon slip model, an ammonia:NO<sub>x</sub> ratio model, and/or a urea hydrolysis model.

An exemplary embodiment includes the amount of the exhaust gas constituent 1106 as an amount of ammonia and an amount of NO<sub>x</sub>, the component performance description 1108 as an ammonia:NO<sub>x</sub> ratio, and the engine parameter adjustment 1110 as a urea injection rate.

Another exemplary embodiment includes the performance analysis module 1102 determining the amount of the exhaust gas constituent 1106, determining the component performance description 1108 as a functionality of an aftertreatment component in response to the amount of the exhaust gas constituent 1106, and the performance feedback module 1104 providing a diagnostic output 1114 in response to the component performance description 1108. The diagnostic output 1114 can be any value indicating the compliance or non-compliance of an aftertreatment component, and may be used by an engine controller to set a malfunction indicator lamp (either ON or OFF), to set a maintenance lamp, to adjust engine controls, to store or clear a fault value, to increment or decrement a fault counter, to trigger additional fault checking or testing, and/or for any other purpose understood in the art.

FIG. 12 is a schematic flow diagram of a technique 1200 for diagnosing a component. The technique 1200 includes an operation 1202 to provide an exhaust stream for an internal combustion engine, the exhaust stream fluidly coupled to an aftertreatment component. The technique 1200 further includes an operation 1204 to optically determine an amount of an exhaust gas constituent in the exhaust stream, and an operation to diagnose an aftertreatment component in response to the amount of the exhaust gas constituent.

Various non-limiting examples of diagnosing an aftertreatment component in response to the amount of the exhaust gas constituent are described herein. One example is an operation 1206 to determine a catalyst effectiveness in response to the amount of the exhaust gas constituent. The catalyst effectiveness may be a catalyst adsorption effectiveness, a catalyst

storage amount, and/or catalyst conversion effectiveness. The catalyst may be an oxidation catalyst, a NO<sub>x</sub> adsorption catalyst, a NO<sub>x</sub> conversion catalyst (e.g. lean NO<sub>x</sub> or selective catalytic reduction), an NO—NO<sub>2</sub> conversion catalyst (a type of oxidation catalyst), or a catalyzed soot filter.

Another example is an operation 1208 to determine whether a soot filter has failed. In one example, the operation 1208 includes determining a soot amount and size downstream of a soot filter, and determining the soot filter has failed if a soot amount or size exceeds a threshold value. In certain embodiments, the operation 1208 includes determining a source of the soot in response to the size of the soot, for example determining whether the soot is normal soot indicating a normal combustion operation, or abnormally sized soot consistent with an exhaust gas recirculation failure, a combustion event failure, a fuel injector failure, an injector 1010 failure where the injector places unburned hydrocarbons in the exhaust stream 1004, and/or a failure of an oxidation catalyst 1006. One of skill in the art can simulate the failures that are to be detected and determine the associated soot size profile as a matter of straightforward data collection.

Another example is an operation 1210 to determine an injector compliance. The injector may inject a reductant or a reagent, and the technique 1200 includes the operation 1210 to determine whether the injector is injecting the scheduled amount, is injecting with an appropriate response time, and/or is injecting with an appropriate geometric distribution in the exhaust stream. In a further embodiment, the technique 1200 includes determining whether the composition of the injected material, e.g. urea, is compliant with expectations, regulations, and/or the system design. For example, the technique 1200 can be utilized to determine whether a reductant vessel has been filled with water rather than urea.

FIG. 15 is a schematic flow diagram of a technique 1500 for modifying a model in response to an amount of an exhaust gas constituent. The technique 1500 includes an operation 1502 to provide an exhaust stream for an internal combustion engine, where the exhaust stream is fluidly coupled to an aftertreatment component. The technique 1500 further includes an operation 1504 to optically determine an amount of an exhaust gas constituent in the exhaust stream, and an operation to modify a model stored on a computer readable medium in response to the amount of the exhaust gas constituent.

Various exemplary and non-limiting operations to modify a model in response to the amount of the exhaust gas constituent are described herein. The modification to the model can include calibrating a modeling parameter, resetting a modeling parameter, and/or resetting an integrator within the model. A modification operation includes the operation 1504 determining an amount of soot and/or NO<sub>x</sub> in the exhaust stream, and an operation 1506 to calibrate an engine soot generation and/or an engine NO<sub>x</sub> generation model in response to the determined amount of soot and/or NO<sub>x</sub>. The operation 1504 to determine the amount of NO<sub>x</sub> may include determining an amount of NO<sub>x</sub> and an amount of NO<sub>2</sub>, where the engine NO<sub>x</sub> generation model may include modeling the amount of NO and the amount of NO<sub>2</sub> separately, and/or modeling a bulk NO<sub>x</sub> output of the engine. Various soot and NO<sub>x</sub> estimators are known in the art that can benefit from real-time calibration.

Another modification operation includes the operation 1504 determining an amount of NO<sub>x</sub>, where the amount of NO<sub>x</sub> is determined after a NO<sub>x</sub>-affecting catalyst and potentially before the NO<sub>x</sub>-affecting catalyst. The modification operation includes an operation 1508 to modifying a catalyst

5

NO<sub>x</sub> storage model, to modify a catalyst NO<sub>x</sub> conversion model, and/or to modify a catalyst NO to NO<sub>2</sub> conversion model.

The operation **1508** to modify the catalyst NO<sub>x</sub> storage model includes determining an actual storage rate based on the observed amounts of NO<sub>x</sub> versus the expected NO<sub>x</sub>, and can include operations such as determining a present storage rate, a total amount of NO<sub>x</sub> stored, a total amount of NO<sub>x</sub> released, and/or a present release rate of NO<sub>x</sub>. Models to estimate NO<sub>x</sub> storage and release are known in the art and can be calibrated based upon NO<sub>x</sub> determinations from a responsive optical sensor that differentiates, for example, NO<sub>x</sub> from NH<sub>3</sub> (ammonia).

The operation **1508** to modify the catalyst NO<sub>x</sub> conversion model includes determining an actual conversion rate based upon the observed amounts of NO<sub>x</sub> versus the expected NO<sub>x</sub>, and potentially further based upon an amount of NH<sub>3</sub> and/or an NH<sub>3</sub>:NO<sub>x</sub> ratio at a NO<sub>x</sub> conversion catalyst. The operation **1508** to modify the catalyst NO to NO<sub>2</sub> conversion model includes determining an actual conversion rate based upon the observed amounts of NO and NO<sub>2</sub> versus the expected amounts of NO and NO<sub>2</sub>. The upstream amounts of NO and NO<sub>2</sub> may be measured or estimated (based upon the characteristics of the engine, for example) and the downstream amounts of NO and NO<sub>2</sub> are measured.

The technique **1500** includes an operation **1510** to determine the exhaust gas constituent at spatially divided portions of the exhaust stream. Referencing FIG. **13**, a cross-section of an exhaust pipe **1302** having an exhaust stream **1004** is shown. A number of optical sensors **1016a**, **1016b**, **1016c** determine an exhaust gas constituent at a number of spatially divided portions of the exhaust stream **1004**. The optical sensors **1016a**, **1016b**, **1016c** may be in any configuration to determine the exhaust gas constituent at any position of interest in the exhaust stream **1004**. The use of various optical sensors **1016a**, **1016b**, **1016c** distributed spatially around the exhaust stream **1004** allows determination of phenomenon such as mal-distribution of a constituent (e.g. an injected constituent that does not distribute completely around the exhaust stream **1004**), puddling of a constituent, and/or accumulation of a constituent.

Referencing FIG. **14**, a number of optical sensors **1016d**, **1016e**, **1016f** determine an exhaust gas constituent at a number of spatially divided portions of the exhaust stream **1004**. The optical sensors **1016d**, **1016e**, **1016f** may be in any configuration to determine the exhaust gas constituent at any position of interest in the exhaust stream **1004**. The use of various optical sensors **1016d**, **1016e**, **1016f** allow determinations of the constituent amount and/or concentration along the axial trajectory of the exhaust stream **104**, and allows determination of phenomenon such as deposition or reaction of a constituent in an aftertreatment component, reaction of the constituent in the exhaust stream **1004** (e.g. hydrolysis of urea from an injector **1010**), and/or removal of a constituent from the exhaust stream **1004** (e.g. un-evaporated droplets attaching to a sidewall of the exhaust stream **1004** at a bend).

In a non-limiting example, urea is injected at the injector **1010** and the optical sensors **1016d**, **1016e**, **1016f** determine whether the urea hydrolyzes in to ammonia. Where the urea remains along the exhaust stream **1004**, hydrolysis determined to be ineffective, where the urea is converted along the exhaust stream **1004**, the amount of urea drops and the amount of ammonia increases and the hydrolysis is determined to be effective. Where the urea disappears along the exhaust stream **1004** but ammonia does not appear, it can be determined that the urea is accumulating along the exhaust stream **1004**, especially where other information indicates

6

that urea evaporation and hydrolysis may be marginal (e.g. where the temperature of the exhaust stream **1004** is low). The amount of hydrolysis detected is utilized, in one embodiment, the technique **1500** includes an operation **1512** to modify a urea hydrolysis model.

One of skill in the art will understand, based on the disclosures herein, that a combination of radially distributed optical sensors **1016a**, **1016b**, **1016c** and axially distributed optical sensors **1016d**, **1016e**, **1016f** can be utilized to develop a three-dimensional picture of exhaust gas constituent distribution in the exhaust stream **1004**.

The detected exhaust gas constituent is urea, and the exhaust gas constituent is detected at a plurality of spatially divided portions of the exhaust stream. The aftertreatment component diagnosis includes diagnosing a urea accumulation condition, urea mal-distribution condition, a urea injector failure condition, and/or a urea hydrolysis failure condition. In certain embodiments, the technique **1500** includes an operation **1514** to diagnose a reductant injector in response to the amount of the exhaust gas constituent. In certain embodiments, the aftertreatment component diagnosis includes diagnosing a composition sensor by determining an amount of the exhaust gas constituent measured by the composition sensor and comparing the reading of the composition sensor to the determined amount of the exhaust gas constituent. For example, the composition sensor can include an oxygen sensor and/or a NO<sub>x</sub> sensor.

Any model calibration or modification operations known in the art are contemplated herein including at least modifying a model parameter value, selecting a model from a list of possible models, and/or resetting a model value such as an integrator. Tuning and modification of models are useful provide better real-time performance of the models and related engine and aftertreatment operations, to determine when a component has degraded or failed, to enhance an On Board Diagnostic, to allow the engine or an aftertreatment component to operate in a more efficient manner and/or to allow the engine or an aftertreatment component to compensate for an off-nominal operating condition.

The descriptions which follow, referencing FIGS. **1** through **9**, include descriptions of exemplary optical sensors capable of performing in an internal combustion engine exhaust environment, including the temperatures, soot, and other chemical constituents normally found in an engine exhaust environment.

FIG. **1** is a schematic diagram of a system **100** for optically determining fluid constituents in challenging environments, including a fluid conduit receiving exhaust gas from an internal combustion engine. In certain embodiments, the system **100** includes an engine **102** having a sample channel (refer to FIG. **2**) comprising a conduit **114** for an engine related fluid. The conduit **114** in the illustration of FIG. **1** is an EGR recirculation path, and the engine fluid in the illustration of FIG. **1** is recirculating exhaust gas flowing in the conduit **114**. In certain embodiments, the conduit **114** may be any conduit having an engine related fluid therein, including, without limitation, an exhaust flow path **106**, an engine intake path, a fuel line, a coolant line, a portion of an intake manifold, and an intake port for an individual cylinder of a multi-cylinder engine. In certain embodiments, the engine related fluid includes engine exhaust gas, engine oil, engine coolant, recirculating exhaust gas, fuel, engine intake gas, and/or engine intake gas corresponding to a single cylinder of a multi-cylinder engine. In certain embodiments, the system further includes a device **112** for determining a concentration of a constituent of the engine fluid. Reference FIG. **2** for details of an exemplary embodiment of the device **112**.

In certain embodiments, the system **100** further includes a controller **118**. The controller **118** is structured to determine a concentration of a component of interest in the engine related fluid. The controller **118** includes communications to sensors and actuators throughout the system **100**, and such communications may be through networks, datalinks, wireless communications, or other communication methods known in the art. The controller **118** may be a single device or distributed devices. In certain embodiments, the controller **118** includes a computer processor and computer readable memory of any known type. In certain embodiments, the controller **118** includes modules structured to functionally execute procedures performed by the controller. The use of the term modules emphasizes the implementation independence of the procedures. Modules may be elements of computer readable code, and may be grouped, divided, and/or distributed among various devices comprising the controller **118**. Reference FIG. **3** for details of an exemplary embodiment of the controller **118**.

In certain embodiments, the component of interest includes a nitrogen-oxygen compound, a hydrocarbon, a sulfur containing compound, ammonia, a compound representative of a natural gas content, a carbon-oxygen compound, and/or an amount of particulates. For example, the compound of interest in certain embodiments includes methane and ethane, and the controller **118** calculates a natural gas content in response to the amount of methane and ethane in the engine related fluid. In certain embodiments, the component of interest includes methane, ethane, and/or propane. In certain embodiments, the component includes nitrogen oxide ( $\text{N}_2\text{O}_x$ ), nitric oxide (NO), nitrogen dioxide ( $\text{NO}_2$ ), and/or nitrous oxide ( $\text{N}_2\text{O}$ ). In certain embodiments, the component of interest includes carbonyl sulfide ( $\text{O}=\text{C}=\text{S}$ ), carbon monoxide, and/or carbon dioxide.

In certain embodiments, the component of interest is component indicative of engine wear, and the controller **118** is further structured to determine an engine wear index in response to the concentration of the component of interest. For example, the compound of interest may be brass (indicative of wear in certain bearings), iron (indicative of wear in certain engine blocks), a material known to be in the piston rings, and/or any other compound that indicates engine wear in a specific application.

In certain embodiments, the component of interest includes a component indicative of fuel quality, and the controller **118** is further structured to determine a fuel quality index in response to the concentration of the component of interest. For example, the compound of interest may be nitrogen which in certain applications is indicative of a filler used in natural gas fuels. The concentration of nitrogen in the natural gas, in certain embodiments, can be indicative of the fuel quality. In another example, the compound of interest may correspond to an additive, tracer, aromatic compound, or other compound in the fuel that in specific applications may be indicative of a quality of the fuel.

In certain embodiments, the engine related fluid includes engine fuel or engine oil, and the component of interest includes sulfur or a sulfur compound. In certain embodiments, the amount of sulfur allowed in the engine fuel and/or engine oil may be regulated, and the controller **118** determines the concentration of sulfur in the fuel and/or oil to provide that information to an engine controller (not shown, but may be included in the controller **118**) for appropriate response.

In certain embodiments, the engine related fluid includes engine oil, and the component of interest comprises one of water and ethylene glycol. In certain embodiments, the pres-

ence of coolant in engine oil may be indicative of certain types of failure, and the controller **118** determines the concentration of sulfur in the fuel and/or oil to provide that information to an engine controller (not shown, but may be included in the controller **118**) for appropriate response.

In certain embodiments, the engine related fluid includes engine coolant, the component of interest includes a component indicative of engine coolant quality, and the controller **118** is further structured to determine an engine coolant quality index in response to the concentration of the component of interest. The engine coolant quality, for example, may be a description of the water/ethylene glycol ratio, and may be utilized by the engine controller (not shown, but may be included in the controller **118**), for example in a warranty assessment after an engine failure.

In certain embodiments, the engine related fluid includes engine oil, the component of interest includes a component indicative of engine oil quality, and the controller is further structured to determine an engine oil quality index in response to the concentration of the component of interest. For example, the component of interest may track the present concentration of an additive in the oil to determine when the oil should be changed. In another example, the component of interest may include a compound or group of compounds from which an API number or other characteristic of the oil may be determined to evaluate the quality of the oil. In certain embodiments, the engine related fluid includes a engine oil, engine fuel, engine coolant, an exhaust gas fluid, a recirculating exhaust gas fluid, and/or an engine intake fluid.

FIG. **2** is a schematic illustration of a device **112** for detecting engine fluid constituents. The device **112** includes an electromagnetic (EM) source **214** structured to emit EM radiation through a first metal tube **206**. The EM radiation includes EM energy at a wavelength of interest. In certain embodiments, the EM energy may be provided by a broad spectrum EM source (e.g. an incandescent source) and passed through an interference filter **210** to remove frequencies outside the wavelength of interest. In certain embodiments, the interference filter **210** is a bandpass filter removing frequencies outside a desired range of frequencies. In certain embodiments, the EM source **214** is a laser that emits the EM radiation at a wavelength of interest and may not include an interference filter **210**. In certain embodiments, the EM source **214** is a tunable laser that emits EM radiation at a number of frequencies of interest, for example to detect a number of components of interest. In certain embodiments, the EM source **214** includes a plurality of source that each emit a different wavelength, or the EM source **214** may be a broad spectrum emitter (e.g. the incandescent source), and a plurality of interference filters **210** allow different wavelength ranges to the first metal tube **206** at different times to detect different components of interest.

In certain embodiments the EM source **214** includes at least one of a laser device, a light emitting diode, and a gallium arsenide light emitting diode. In certain embodiments, the device **112** includes the interference filter **210** disposed between the EM source **214** and the sample channel **114**, with the interference filter **210** including a band pass filter. In certain embodiments, the first metal tube **206** and the second metal tube **208** each comprise extruded aluminum, extruded stainless steel, a polished metal, and/or a machined metal. The tubes **206**, **208** should have sufficient resistance to temperature and corrosion in the system **100**, and have sufficient internal reflectivity to convey the EM radiation to the sample channel **114** and back from the sample channel **114**.

In certain embodiments, the device **112** further includes an EM detector **212** structured to receive a remainder radiation

through a second metal tube **208**, the remainder radiation including the remaining EM energy of the EM radiation after passing through the sample channel **114**. In certain embodiments, the second metal tube **208** may be the same physical tube as the first metal tube **206**, for example the EM radiation may pass through the first metal tube **206**, reflect off a mirror opposing the entrance of the first metal tube **206**, and pass back into the first metal tube **206**, which is then acting as the second metal tube **208**, back to the EM detector **212**. In certain embodiments, the EM detector **212** includes a lead selenide detection device.

In certain embodiments, the device **112** includes a first window **202** isolating the first metal tube **206** from the sample channel **114**, and a second window **204** isolating the second metal tube **208** from the sample channel **114**. The window material should be selected to allow sufficient EM energy through the window **202**, **204** at the wavelength of interest that the EM detector **212** can distinguish the concentration of the component of interest through the expected operational range for the component of interest, or the portion of the expected operational range that is of interest. For example, if the component of interest is oxygen in an internal combustion engine application, the expected range may be zero to twenty-one percent oxygen by mole, or a lower range if, for example, values above a certain percentage are not of interest in a particular application.

Factors that affect the final strength of the received EM radiation include the available power of the EM source **214**, losses in the interference filter **210**, tubing **206**, **208**, the strength of the extinction response of the component of interest at the selected wavelength, and the optical path length across the sample channel **114**. The material of the window **202**, **204** should further be a material that withstands the thermal and chemical environment of the conduit **114**, and further that can suitably conduct heat to allow a cleaning event (e.g. reference FIGS. **3** and **9**, and related descriptions) and withstand the cleaning temperature of the cleaning event. The selection of a specific window material is dependent upon the application and is a mechanical step for one of skill in the art based upon the disclosures herein. In certain embodiments, the first window **202** and the second window **204** comprise a material selected from the group consisting of sapphire, glass, and diamond. In one example, the component of interest is carbon dioxide, the engine related fluid includes combustion exhaust gases, the wavelength of interest is about 4.26 $\mu$ m, the sample channel **114** has an optical path length of about 35 mm, and the window **202**, **204** material is sapphire.

In certain embodiments, the first window **202** and the second window **204** are the same physical window, for example where the first metal tube **206** and the second metal tube **208** are the same physical tube. In certain embodiments, the device **112** includes a reflective device (e.g. a mirror, not shown) opposing the first window **202**, for example where the first metal tube **206** and the second metal tube **208** are the same physical tube.

In certain embodiments, the system further includes a kit (e.g. as a portion of the device **112**) having the first metal tube **206**, the second metal tube **208**, the first window **202**, the second window **204**, and at least a portion of the sample channel **114**. In certain embodiments, the kit further includes means for quick removal and replacement. For example, the kit may include wing nuts, levered clamps, seals, and/or other quick disconnect devices to allow ready removal of the kit and installation of a replacement kit. In certain embodiments, means for quick removal and replacement further includes positioning of the device **112** within a system at a location where access is readily available—for example positioning

the device where the starter, turbocharger **110**, fan, or other components in the application are not blocking access to the kit.

FIG. **3** is a schematic diagram of a controller **118** structured to determine a concentration of a component of interest. In certain embodiments, the controller **118** is structured to determine a composition indicator signal **310** in response to a strength of the remainder radiation and determine a concentration of a component of interest **346** according to the composition indicator signal **310**. For example, an EM detector **212** receives the EM remainder radiation, the controller **118** determines the composition indicator signal **310** based on the strength of the remainder radiation, and determines the concentration of a component of interest **346** according to the composition indicator signal **310**.

In certain embodiments, a controller **118** includes an electromagnetic (EM) source control module **302** structured to provide an EM pulse signal **340**. In certain embodiments, the EM source **214** emits EM radiation through the first metal tube **206** and the sample channel **114** in response to the EM pulse signal **340**. In certain embodiments, the EM detector **212** receives the EM radiation from the sample channel **114** through a second metal tube **208**, and provides a composition indicator signal **310** in response to a remaining radiation strength at the wavelength of interest. In certain embodiments, the controller **118** includes a composition determination module **304** that determines a concentration of a component of interest **346** according to the composition indicator signal **310**. For example, in certain embodiments, the composition indicator signal **310** may be an extinction value at the wavelength of interest, and the composition determination module **304** may utilize a lookup table that determines the concentration of a component of interest **346** as a function of the extinction value. The lookup table is calibrated according to the system **100** that the device **112** is installed in.

In certain embodiments, the EM source control module **302** provides an EM diagnostic signal **342**, and the EM source **214** emits an EM diagnostic radiation in response to the EM diagnostic signal. The EM diagnostic radiation includes energy at a diagnostic wavelength, and the EM detector **212** provides a received diagnostic signal **312** in response to a remaining EM diagnostic radiation strength at the diagnostic wavelength. The diagnostic wavelength is a wavelength selected such that no expected components of the engine related fluid significantly absorb the diagnostic wavelength, except for “grey” or “black” components (e.g. components that absorb all wavelengths roughly equivalently). In many circumstances, soot in the engine related fluid and debris deposited on the windows **202**, **204** can be treated as grey matter with sufficient accuracy for many purposes.

In certain embodiments, the controller **118** further includes a diagnostic module **306** that determines an amount of soot **348** in response to the received diagnostic signal **312**. In certain embodiments, the amount of soot **348** is determined by attributing an entire diagnostic signal **312** strength loss, relative to a baseline diagnostic signal **312** strength, to absorption by soot in the engine related fluid. In certain embodiments, the diagnostic module **306** determines an amount of debris **350** deposited on the windows (**202**, **204**), determines a diagnostic signal **312** strength loss attributable to the amount of debris **350**, and determines a remainder of the diagnostic signal **312** strength loss as attributable to the amount of soot **348**.

In certain embodiments, the composition determination module **304** determines the concentration of the component of interest **346** according a corrected composition indicator signal **316**. In certain embodiments, the composition deter-

11

mination module **304** determines the corrected composition indicator signal **316** according to the equation:

$$CCIS = \frac{\text{Active} - \text{Dark}}{\text{Inactive} - \text{Dark}} \quad (\text{Equation 1})$$

In the example Equation 1, CCIS is the corrected composition indicator signal **316**, Active is the composition indicator signal **310**, Inactive is the received diagnostic signal **312**, and Dark is a detected response at a time when the EM source **214** is not emitting EM radiation. For example, if the composition indicator signal **310** shows 70% (i.e. 30% absorption of the wavelength of interest), the received diagnostic signal **312** shows 90%, and the baseline response with the EM source **214** turned off is 2%, the composition indicator signal **310** is a value based on 70% while the corrected composition indicator signal **316** is a value based on  $((70-2)/(90-2))$  is 77%, or a little stronger than the directly indicated composition indicator signal **310** due to suppression of the signal by an amount of soot **348** and/or an amount of debris **350**.

In certain embodiments, the diagnostic module **306** determines the amount of soot **348** by filtering the received diagnostic signal **312** with a time constant less than 30 seconds to provide an Inactive fast response signal **318**, filtering the received diagnostic signal **312** with a time constant greater than 30 seconds to provide an Inactive slow response signal **320**, and determining the amount of soot **348** according to the Inactive slow response signal **320** subtracted from the Inactive fast response signal **318**. The 30-second value is exemplary only. The Inactive fast response signal **318** is an indicator of total grey matter in the conduit **114** (i.e. soot plus debris) and the inactive slow response signal **320** is an indicator of long term grey matter in the conduit **114** (i.e. debris only). In certain embodiments, the inactive slow response **320** utilizes a relatively slow rising time constant and a relatively fast falling time constant, to bias the inactive slow response **320** to a lower value in the observed range of inactive values (i.e. of received diagnostic signal **312** values). In certain embodiments, diagnostic module determines an amount of debris **350** accumulated on the window(s) **202**, **204** according to a lowest Inactive value **322** observed over time. For example, the diagnostic module **306** may track received diagnostic values **312**, and reset the inactive lowest value **322** to the lowest observed value over a recent period—for example a lowest value observed in the last five minutes, or a lowest value observed during the most recent engine motoring event (i.e. when the engine was last not combusting any fuel).

In certain embodiments, the controller **118** further includes a window cleaning module **308** that provides a window cleaning index value **326** in response to the amount of debris **350** accumulated. In certain embodiments, the window cleaning module **308** is further structured to provide a window cleaning request signal **344** in response to the window cleaning index value **326** exceeding a cleaning threshold value **328**. In certain embodiments, the system **100** includes a window cleaning means that cleans the window(s) in response to the window cleaning request signal **344**.

In certain embodiments, the diagnostic module **306** determines a fault value **330**, an engine wear index **332**, a fuel quality index **334**, an engine coolant quality index **336**, and/or an engine oil quality index **338** in response to the concentration of the component of interest **346**. In certain embodiments, the fault value **330** is an indication whether an engine **102** parameter is out of tolerance according to the concentration(s) of the component(s) of interest **346**. In certain embodi-

12

ments, the indices **332**, **334**, **336**, **338** provide a value correlated to the underlying engine parameter—i.e. engine wear, fuel quality, engine coolant quality, and/or engine oil quality—according to the concentration(s) of the component(s) of interest **346**.

FIG. **4** is an illustration **400** of a constituent wavelength response. The illustration **400** includes a response value **412** versus a wavelength (or possibly frequency) value **414** for a component of interest. The constituent wavelength response illustrated in FIG. **4** is consistent with a simplified illustration for carbon dioxide, showing a first responsive wavelength **408** and a second, stronger, responsive wavelength **410**. Depending upon the parameters of the system **100** (refer to the section referencing FIG. **2**), a wavelength of interest for the EM radiation from the EM source **214** may be selected at either responsive wavelength **402**, **404**. In certain embodiments, the sample channel **114** may be too long, or the constituent concentrations expected may be too high, such that instead of using the stronger response wavelength **410**, the weaker response wavelength **408** may be selected.

In certain embodiments, the wavelength of interest may be selected as one of the responsive wavelengths, for example selecting wavelength **402** and/or **404**. In certain embodiments, the wavelength of interest may be selected as a wavelength near one of the responsive wavelengths, for example selecting wavelength **406**. In certain embodiments, the wavelength of interest such that an extinction of the wavelength of interest is about 50% of an extinction of the responsive wavelength near the wavelength of interest (e.g. about what the wavelength of interest **406** indicates in FIG. **4**). The extinction of the responsive wavelength may be measured as a peak value (e.g. a discrete value right on the responsive wavelength **408**), or as an area under (or above) a range of wavelength values, such as a range of values allowed through the band-pass filter **210**.

The selection of an off-nominal wavelength such as the wavelength of interest **406** allows for longer sample channel **114** lengths, detection at higher constituent concentrations, and similar adjustments. The wavelength of interest may be variable or multiple in certain embodiments, for example providing higher extinction rates at lower constituent concentrations and lower extinction rates at higher constituent concentrations, or providing higher and lower extinction rates at all times and utilizing both extinction rates in calculating a composition indicator signal **310**. In certain embodiments, the responsive wavelength includes a fundamental wavelength and/or a harmonic wavelength.

The schematic flow diagrams (FIGS. **5-9**) and related descriptions which follow provide illustrative embodiments of operations related to the present application. Operations shown are understood to be illustrative only, and operations may be combined or divided, and added or removed, as well as re-ordered in whole or part, unless stated explicitly to the contrary herein.

FIG. **5** is a schematic flow diagram of a procedure **500** for determining a concentration of a component of interest. In certain embodiments, the procedure **500** includes an operation **502** to isolate the first metal tube from the sample channel with a first window and isolating the second metal tube from the sample channel with a second window. In certain embodiments, the procedure **500** further includes an operation **504** to select a wavelength of interest, and an operation **506** to select a diagnostic wavelength.

The procedure **500** includes an operation **508** to flow an engine related fluid through a sample channel, and an operation **510** to emit an electromagnetic (EM) radiation comprising energy at a wavelength of interest through a first metal

13

tube. The procedure **500** further includes an operation **512** to pass the EM radiation through a bandpass filter. The procedure **500** further includes an operation **514** to pass the EM radiation through the sample channel and an operation **516** to receive the radiation at an EM detector through a second metal tube. The procedure **500** further includes an operation **518** to determine a composition indicator signal in response to a remaining radiation strength at the wavelength of interest.

In certain embodiments, the procedure **500** includes an operation **520** to emit an EM diagnostic radiation comprising energy at a diagnostic wavelength, and an operation **522** to receive the remaining diagnostic radiation strength at the diagnostic wavelength at an AM detector. In certain embodiments, the procedure **500** further includes an operation **524** to determine a diagnostic signal in response to the remaining diagnostic radiation strength at the diagnostic wavelength. In certain embodiments, the procedure **500** further includes an operation **526** to determine a corrected composition indicator signal. The procedure further includes an operation **528** to determine a concentration of a component of interest according to the composition indicator signal by utilizing the corrected composition indicator signal. In certain embodiments, the procedure **500** further includes an operation **530** to check for whether concentrations should be determined for further components. In response to a determination that concentrations should be determined for further components, the procedure **500** includes operations **510-528** to emit EM radiation at a second (or third, fourth . . . etc.) wavelength of interest, and to determine a concentration of a second component of interest in response to the EM radiation at the second wavelength of interest.

FIG. 6 is a schematic flow diagram of a procedure **600** for designing an apparatus for determining a concentration of a component of interest. The procedure **600** includes an operation **602** to determine a path length across a sample channel, and an operation **604** to determine extinction rates corresponding to responsive wavelengths for a component of interest at a design range of concentration. The procedure **600** further includes an operation **606** to select a frequency of interest according to the extinction rates corresponding to the responsive frequencies for the component of interest at the design range of concentrations of the component of interest. In certain embodiments, the procedure **600** includes an operation **500** to determine a concentration of a component of interest, for example utilizing one or more operations from the procedure **500**.

FIG. 7 is a schematic flow diagram of a procedure **700** for replacing an apparatus for determining a concentration of a component of interest. In certain embodiments, the procedure **700** includes an operation **702** to provide a replacement kit comprising the first metal tube, the second metal tube, the first window, and the second window, and operations **704** including removing a previously installed kit from an engine. The procedure **700** further includes an operation **706** to install the replacement kit on the engine. In certain embodiments, the procedure **700** includes an operation **500** to determine a concentration of a component of interest, for example utilizing one or more operations from the procedure **500**.

FIG. 8 is a schematic flow diagram of a procedure **800** for determining a plurality of fluid indices. In certain embodiments, the procedure **800** includes an operation **500** to determine a concentration of a component of interest, for example utilizing one or more operations from the procedure **500**. In certain embodiments, the procedure **800** further includes an operation **802** to determine whether a debris determination method includes an inactive slow response or an inactive low amount. In response to the procedure **800** including the inac-

14

tive slow response, the procedure **800** includes an operation **804** to determine an inactive slow response, and an operation **808** to determine a debris amount in response to the inactive slow response. In response to the procedure **800** including an inactive low amount, the procedure **800** includes an operation **806** to determine an inactive low amount, and an operation **808** to determine a debris amount in response to the inactive low amount.

In certain embodiments, the procedure **800** includes an operation **810** to determine a window cleaning index value in response to the amount of debris accumulated. In certain embodiments, the procedure **800** further includes an operation **812** to determine whether the window cleaning index is greater than a cleaning threshold. In certain embodiments, the procedure **800** includes an operation **814** to perform a window cleaning event in response to determining the window cleaning index value exceeds a cleaning threshold value. In certain embodiments, the procedure includes an operation **816** to determine a fault value in response to the received diagnostic signal. In certain embodiments, the procedure **800** includes an operation **818** to determine an engine wear index **818**, an operation **820** to determine a fuel quality index, an operation **822** to determine an engine coolant quality index, and/or an operation **824** to determine an engine oil quality index in response to the concentration(s) of the component(s) of interest.

FIG. 9A is a schematic diagram of an apparatus for cleaning an optical element. The apparatus **900** includes the optical element **202** and a means for cleaning the optical element. In certain embodiments, the apparatus **900** includes a wire **902** with a high thermal expansion coefficient, and the wire is positioned to sweep the optical element **202** upon a temperature increase event. In certain embodiments, the wire **902** may be a resistive wire that heats when a supply voltage **904** is applied, sweeping the wire **902** across the optical element **202**.

FIG. 9B is a schematic diagram of an apparatus for cleaning on optical element. The apparatus **901** includes the optical element **202**, which may be a sapphire cylinder. In certain embodiments, and a tube **206**. In certain embodiments, a ceramic filler **908** or other heat resistant material provides a seal between the optical element **202** and the conduit **114**. The apparatus **901** includes a means for cleaning the optical element **202** including a resistive wire **905** wrapped around a portion of the optical element **202**, such that when the resistive wire **905** is heated the face of the optical element **202** exposed to the conduit **114** (i.e. the "window") is heated sufficiently to drive debris (through oxidation, evaporation, or other means) from the face of the optical element **202**. A supply voltage **904** may be applied to the resistive wire **905** at times where a cleaning event is performed.

FIG. 9C is a schematic diagram of an apparatus **903** for cleaning an optical element. The apparatus **903** includes a resistive wire **910** in thermal contact with a mirror **912** positioned opposite an optical element **202**. The resistive wire **910** heats the mirror **912** sufficiently to drive debris (through oxidation, evaporation, or other means) from the face of the mirror **912**. A supply voltage **904** may be applied to the resistive wire **910** at times where a cleaning event is performed.

As is evident from the Figures and text presented above, a variety of embodiments according to the present invention are contemplated. Certain exemplary embodiments of methods and apparatus for diagnosing an aftertreatment component, for adjusting an engine operating parameter in response to a component performance description of an aftertreatment

15

component, and for modifying a model stored on a computer readable medium are described. All embodiments are exemplary and non-limiting.

An exemplary method includes providing an exhaust stream for an internal combustion engine, the exhaust stream fluidly coupled to an aftertreatment component, optically determining an amount of an exhaust gas constituent in the exhaust stream, and diagnosing an aftertreatment component in response to the amount of the exhaust gas constituent. In one embodiment, the exhaust gas constituent includes  $\text{NO}_x$ , and diagnosing the aftertreatment component includes determining a catalyst effectiveness. The catalyst effectiveness may be a catalyst adsorption effectiveness and/or a catalyst conversion effectiveness.

In certain embodiments, the exhaust gas constituent is soot. The exemplary method further includes diagnosing the aftertreatment component by determining that a soot filter has failed, and/or by determining a size of the soot. The method further includes determining a source of the soot in response to the size of the soot.

In an exemplary embodiment, the exhaust gas constituent includes NO (nitrogen-oxide), the method includes determining an amount of  $\text{NO}_2$ , and diagnosing the aftertreatment component includes determining a catalyst NO to  $\text{NO}_2$  conversion effectiveness. In another exemplary embodiment, the exhaust gas constituent includes urea, and diagnosing the aftertreatment component includes determining a urea injector compliance and/or diagnosing an injected urea composition.

In certain embodiments, the exhaust gas constituent is urea, and the method further includes determining the exhaust gas constituent at a plurality of spatially divided portions of the exhaust stream. Diagnosing the aftertreatment component further includes diagnosing a urea accumulation condition, urea mal-distribution condition, a urea injector failure condition, and/or a urea hydrolysis failure condition. In certain embodiments, the method includes diagnosing the aftertreatment component by diagnosing a composition sensor.

Another exemplary embodiment is an apparatus including an optical sensor structured to determine an amount of an exhaust gas constituent in an exhaust stream of an internal combustion engine, a performance analysis module that determines a component performance description in response to the amount of the exhaust gas constituent, and a performance feedback module that adjusts an engine operating parameter in response to the component performance description. The apparatus includes the component performance description as a functional performance description of a physical component. The physical component includes a  $\text{NO}_x$  adsorption catalyst, a  $\text{NO}_x$  conversion catalyst, an NO— $\text{NO}_2$  conversion catalyst, an oxidation catalyst, a soot filter, and/or a reductant injector. In certain embodiments, the functional performance description includes a catalyst conversion efficiency value, a catalyst storage capacity value, a filter integrity value, and/or an injection compliance value.

In certain embodiments, the component performance description includes a functional performance description of a model, and the performance feedback module further adjusts an engine operating parameter by modifying the model. The model includes an engine-out soot model, an engine-out  $\text{NO}_x$  model, an engine-out  $\text{NO}_x$  composition model, a  $\text{NO}_x$  adsorption model, a  $\text{NO}_x$  release model, a  $\text{NO}_x$  conversion model, a hydrocarbon oxidation model, an ammonia slip model, an unburned hydrocarbon slip model, and/or a urea hydrolysis model. The exhaust gas constituent includes an amount of ammonia and an amount of  $\text{NO}_x$ , where the

16

component performance description includes an ammonia:  $\text{NO}_x$  ratio, and the engine operating parameter includes a urea injection rate.

Another exemplary embodiment is a method including providing an exhaust stream for an internal combustion engine, the exhaust stream fluidly coupled to an aftertreatment component, optically determining an amount of an exhaust gas constituent in the exhaust stream, and modifying a model stored on a computer readable medium in response to the amount of the exhaust gas constituent. The modifying the model includes calibrating a modeling parameter, resetting a modeling parameter, and/or resetting an integrator. In an exemplary embodiment, the exhaust gas constituent includes soot, and modifying the model includes calibrating an engine soot generation model.

In certain embodiments, the exhaust gas constituent includes  $\text{NO}_x$ , and modifying the model includes calibrating an engine  $\text{NO}_x$  generation model, modifying a catalyst  $\text{NO}_x$  storage model, modifying a catalyst  $\text{NO}_x$  conversion model, and modifying a catalyst NO to  $\text{NO}_2$  conversion model. In certain embodiments, the exhaust gas constituent includes urea, and the method further includes determining the exhaust gas constituent at a number of spatially divided portions of the exhaust stream. Modifying the model further includes modifying a urea hydrolysis model.

While the invention has been illustrated and described in detail in the drawings and foregoing description, the same is to be considered as illustrative and not restrictive in character, it being understood that only certain illustrative embodiments have been shown and described and that all changes and modifications that come within the spirit of the inventions are desired to be protected. It should be understood that any relative characterization of embodiments such as but not limited to preferable, preferably, preferred, more preferred, advantageous, or exemplary utilized in the description above indicate that the embodiments or features thereof so described may be more desirable or characteristic, nonetheless the embodiments or features thereof may not be necessary and embodiments lacking the same may be contemplated as within the scope of the invention, the scope being defined by the claims that follow. In reading the claims, it is intended that when words such as “a,” “an,” “at least one,” or “at least one portion” are used there is no intention to limit the claim to only one item unless specifically stated to the contrary in the claim. When the language “at least a portion” and/or “a portion” is used the item can include a portion and/or the entire item unless specifically stated to the contrary.

What is claimed is:

1. A method comprising:

- providing an exhaust stream for an internal combustion engine, the exhaust stream fluidly coupled to an aftertreatment component;
- optically determining an amount of exhaust gas constituents in the exhaust stream during the operation of the internal combustion engine, the exhaust gas constituents comprising urea, NO,  $\text{NO}_2$  and soot;
- diagnosing the aftertreatment component in response to the amount of the exhaust gas constituents; and
- wherein diagnosing the aftertreatment component comprises:
  - determining that a soot filter has failed in response to the optically determined amount of soot; and
  - determining a catalyst NO to  $\text{NO}_2$  conversion effectiveness of an oxidation catalyst in response to the optically determined amount of NO and  $\text{NO}_2$ .



17

2. The method of claim 1, wherein the exhaust gas constituents further comprise  $\text{NO}_x$ , and wherein diagnosing the aftertreatment component comprises determining a catalyst effectiveness.

3. The method of claim 1, wherein diagnosing the aftertreatment component further comprises determining a urea injector compliance.

4. The method of claim 1, wherein diagnosing the aftertreatment component further comprises diagnosing an injected urea composition.

5. The method of claim 1, wherein the diagnosing the aftertreatment component further comprises diagnosing a composition sensor.

6. The method of claim 1, further comprising determining a size of the soot.

7. The method of claim 6, wherein diagnosing the aftertreatment component comprises determining that the soot filter has failed in response to the size of the soot exceeding a threshold value.

8. The method of claim 1, further comprising determining the exhaust gas constituents at a plurality of spatially divided portions along the exhaust stream and a plurality of radially divided portions around the exhaust stream.

9. The method of claim 8, wherein diagnosing the aftertreatment component comprises diagnosing at least one condition selected from the conditions consisting of: urea accumulation, urea mal-distribution, a urea injector failure, and a urea hydrolysis failure.

10. An apparatus, comprising:

a number of optical sensors structured to determine an amount of an exhaust gas constituent in an exhaust stream of an internal combustion engine during the operation of the internal combustion engine, wherein the number of optical sensors are spatially distributed along the exhaust stream to detect the amount of the exhaust gas constituent along the exhaust stream, the exhaust gas constituent comprising an amount of urea; and

a controller including a computer processor and a computer readable memory including computer readable code, wherein when the computer readable code is executed by the computer processor it causes the controller to:

determine an aftertreatment component diagnosis in response to the amount of urea along the exhaust stream; and

modify a urea hydrolysis model to adjust an engine operating parameter in response to the aftertreatment component diagnosis,

18

wherein the aftertreatment component diagnosis comprises at least one of a urea accumulation condition, a urea mal-distribution condition, a urea injector failure condition, and a urea hydrolysis failure condition.

11. The apparatus of claim 10, wherein the controller is further structured to diagnose an injected urea composition in response to the exhaust gas constituent.

12. The apparatus of claim 10, wherein the number of optical sensors are further positioned to sense radially divided portions of the exhaust stream.

13. The apparatus of claim 12, wherein the number of optical sensors includes at least three optical sensors radially distributed about the exhaust stream.

14. An apparatus, comprising:

an optical sensor structured to determine an amount of an exhaust gas constituent in an exhaust stream of an internal combustion engine during the operation of the internal combustion engine, the exhaust gas constituent comprising an amount of ammonia and an amount of  $\text{NO}_x$ ; and

a controller including a computer processor and a computer readable memory including computer readable code, wherein when the computer readable code is executed by the computer processor it causes the controller to:

determine a component performance description in response to the amount of the exhaust gas constituent determined by the optical sensor, wherein the component performance description includes an ammonia: $\text{NO}_x$  ratio; and

modify at least one of a catalyst  $\text{NO}_x$  storage model and a catalyst  $\text{NO}_x$  conversion model of a  $\text{NO}_x$  conversion catalyst in response to an actual  $\text{NO}_x$  storage rate based on the amount of  $\text{NO}_x$  determined by the optical sensor and the ammonia: $\text{NO}_x$  ratio to adjust an engine operating parameter in response to the component performance description,

and wherein the engine operating parameter comprises a urea injection rate.

15. The apparatus of claim 14, wherein the optical sensor includes a number of optical sensors radially distributed around the exhaust stream to sense radially divided portions of the exhaust stream and axially distributed along the exhaust stream to sense axially divided portions of the exhaust stream.

\* \* \* \* \*